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SOIL STRENGTH–ROOT PENETRATION RELATIONS FOR MEDIUM- TO COARSE-TEXTURED SOIL MATERIALS

HOWARD M. TAYLOR, GENE M. ROBERSON, AND JESSIE J. PARKER, JR.

United States Department of Agriculture[1]

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For seedlings to grow, their hydrostatic pressure (turgor) must be sufficient to overcome internal restraints imposed by cell structures plus mechanical restraints imposed by the surrounding media (1, 2). If the surrounding media is gaseous or liquid, the additional resistance to growth is negligible. If, however, soil surrounds the plant part, growth can be inhibited or even prohibited by the additional restraint.

Taylor and Gardner (4) used soil-strength measurements as indicators of resistance encountered as seedling cotton taproots penetrated soil. In laboratory experiments, they found that the percentage of cotton taproots penetrating through cores of Amarillo fine sandy loam soil decreased progressively as penetrometer soil strength increased until, at about 30 bars strength, no roots penetrated. In field experiments, Taylor and Burnett (5) found that no cotton roots penetrated Amarillo soil pans with strengths greater than 25 bars measured at field capacity with a penetrometer. Considerable rooting, however, occurred through a soil layer with a strength of 19 bars at field capacity.

This paper presents a working hypothesis to extrapolate results obtained using Amarillo soil to other soil materials. The hypothesis is: Provided no other growth factor becomes limiting, a specific change in soil strength will cause a specific response of underground portions of a plant regardless of the source of soil material. As a corollary, it is recognized that soil strength levels may become prohibitive and allow neither penetration nor expansion of plant parts.

The research reported here provided an initial test of this working hypothesis. This paper presents the effects of soil strength on cotton taproot penetration through cores of four other medium- to coarse-textured soil materials, and discusses some consequences of substantiated portions of the hypothesis.

MATERIALS AND METHODS

Experimental soils

Soils were collected from widely separated sites in semiarid environments within the United States. Miles loamy fine sand was collected from a wind-sorted A_p horizon of a soil developed on wind and water sediments in the Rolling Red Plains of Texas. Naron fine sandy loam soil was collected from the wind-sorted A_p horizon of a soil developed on wind and water sediments in southwestern Kansas. Quinlan very fine sandy loam was collected about 3 meters below the surface in loosely consolidated material of a Permian formation in the Rolling Plains of Texas. The Quinlan soil is very low in available phosphorus, nitrogen, and organic matter. The Columbia loam soil was collected from a recent deposit on the Mokelumne River in the Central Valley of California. This sample contained large quantities of sand- and silt-sized mica-like particles. Mechanical analyses by the pipette method, cation-exchange capacities by the sodium acetate method, and organic carbon by the wet oxidation method are listed in table 1 for the four soils.

EXPERIMENTAL PROCEDURE

The procedure was similar to that of Taylor and Gardner (4). Soil cores, 2.54 cm. in final height and 4.02 cm. in diameter, were compressed (initial soil suction was ⅓ bar) to known bulk densities in steel retainer rings, rewetted, and equilibrated to known soil suctions ranging from ⅙ to 1 bar. The specific bulk densities and soil suctions for each soil are presented in figure 1. For each soil, 22 compressed cores of each bulk density and soil suc-

[1] Soil and Water Conservation Research Division, Agricultural Research Service, in cooperation with the Texas Agricultural Experiment Station.

tion were prepared. Twelve of the cores were used to determine root penetration and ten were used as controls to determine soil strengths and moisture contents at the time of planting. There were never more than two cores of a particular soil series and bulk density on any one pressure plate during an equilibration period.

In the test for root penetration, five cotton seeds (*Gossypium hirsutum* L. variety Western Stormmaster) were placed on a core surface and covered with 2 cm. of loose soil in a second retainer ring. The loose cover soil, which was at the same soil suction as the compressed core, was then compressed with a 0.6-bar stress. Sets of 20 planted core assemblies were placed in an enclosed plastic chamber to suppress evaporation. After a 7-day period of 27 ± 1°C., the number of taproots that had penetrated the 2.54-cm.-thick cores was recorded.

On each of the 10 control cores, triplicate measurements of soil strength were made with a force-gauge penetrometer[2] by forcing a 0.48-cm.-diameter tip 0.5 cm. into the soil surface. To check for possible pressure-plate-apparatus leaks, soil moisture contents were determined gravimetrically by drying subsamples at 104°C.

RESULTS

Figure 1 presents effects of the various combinations of soil bulk density and soil suction on soil strength as measured by a force gauge penetrometer. The four soils show similar general patterns. Soil strength increases as soil bulk density or soil suction increases; when, however, the four soils are compared at a specific soil bulk density and soil suction, there are large differences among the resultant soil strengths. As an example, compare the strengths of the four soils at ⅓-bar soil suction and a bulk density of 1.55 g./cm.[3]. Under these stated conditions, strength of Columbia loam soil is 19 bars, that of Miles loamy fine sand is 6 bars, that of Naron fine sandy loam is 7 bars, and that of Quinlan very fine sandy loam is 9 bars. When the soils are compared at a soil suction of ⅓-bar and a bulk density of 1.80 g./cm.[4], strength of Miles loamy fine sand is 17 bars, Naron fine sandy loam is 21 bars, and Quinlan very fine sandy loam is 30 bars. Data are not available for Columbia loam.

The percentage of taproots that penetrated the soil cores decreased as soil strength in-

TABLE 1
Characteristics of soils used

Soil Type	Site Location	Mechanical Analysis: Sand >50μ	Silt 50-2μ	Clay <2μ	Organic Carbon %	Cation-Exchange Capacity
		%				*me./100 g. soil*
Miles loamy fine sand	Roby, Fisher Co., Texas	83	8	9	0.2	6
Naron fine sandy loam	Pratt, Pratt Co., Kansas	79	11	10	0.4	7
Quinlan very fine sandy loam	Memphis, Hall Co., Texas	73	20	7	0.02	8
Columbia loam	Clements, San Joaquin Co., California	44	37	19	1.3	14

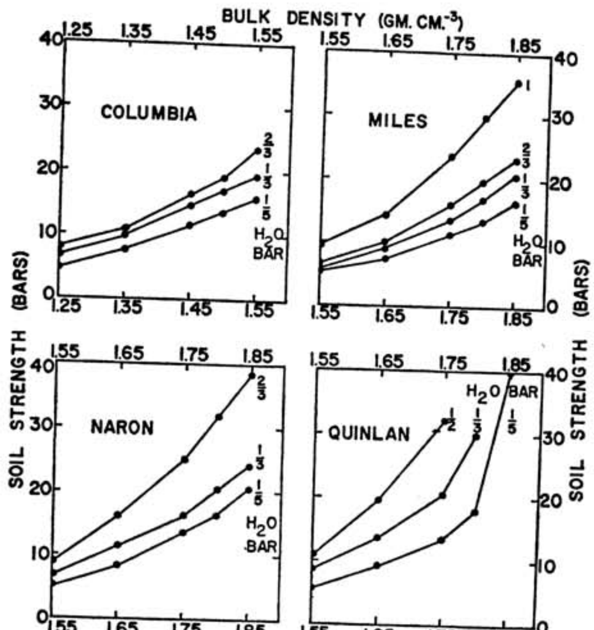

FIG. 1. Relations among the bulk density, soil suction, and penetrometer strength of four soils.

[2] Model 719-40, John Chatillon & Sons, 85 Cliff Street, New York, N. Y. (Product and Company name is included for the benefit of the reader and does not imply any endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.)

[3] Unpublished data, U. S. Dep. Agr., Big Spring Field Station, Big Spring, Texas.

[4] *Ibid.*

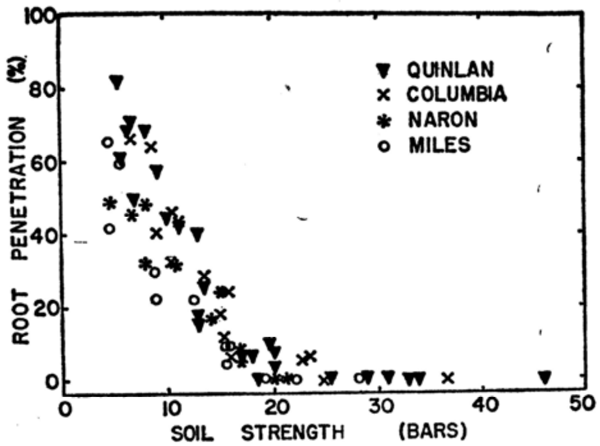

FIG. 2. Relation between the penetrometer soil strength and percentage of cotton taproots penetrating through cores of four soils.

creased (fig. 2). Although slight differences among soil series may be noted, all four soils showed the same curvilinear trend. A sharp decline in root penetration percentage occurred as soil strengths increased from 3 to 15 bars and then a more gradual decline occurred to about 25 bars strength. No taproots penetrated any core with a strength of 25 bars or greater, regardless of the soil series.

Root penetration was evaluated as a function of soil moisture content, soil suction, air-filled porosity, and soil bulk density. These relations, however, simply further verify the conclusions of Taylor and Gardner (4) that soil strength is the critical factor controlling cotton seedling root penetration through Southern Great Plains soils at soil suctions of ⅕ to 1 bar, and are not, therefore, reported.

When the results of this experiment are compared with those of the previous experiment by Taylor and Gardner (4), two differences become apparent: (*a*) the strength at which no roots penetrated the soil cores was slightly lower in the present experiment, and (*b*) in the present experiment, since the initial incremental increases in soil strength caused the greatest decreases in root penetration percentages, the data exhibit a curvilinear trend rather than the linear trend they (4) reported.

A separate phase of the present experiment determined if the difference between the soil strength–root penetration relation for Amarillo soil and that for the other four soils was real or an artifact. Cores of Amarillo fine sandy loam soil were brought to bulk densities and moisture contents used in the original study (4), and soil strengths were determined immediately after equilibration. In the original study, control cores and planted cores were enclosed together in a plastic chamber for 10 days before soil strengths were determined. Aging or moisture transfer could have altered soil strengths. When the new strength data were combined with the original root penetration percentages, the data fell within the same general limits as those reported here for the other four soils. The relation between strength of Amarillo soil and root penetration, therefore, probably did not differ from the relation presented in this paper.

There are valid arguments both for and against using penetrometer measurements as indicators of soil strength. Figure 3 presents the relation between penetrometer soil strength (as used in this paper) and vane shear strength. In obtaining this relation, the laboratory vane was inserted into unloaded soil until the top of the vane was level with undisturbed soil surface. There is a linear relation between soil strengths measured by the two methods. When, however, penetrometer soil strengths of 10 bars were measured, vane shear strengths were about 0.4 bar.

DISCUSSION

As shown in figure 3, reported values of soil strength depend upon which of the many available procedures is used to measure strength. When a particular procedure is used, however, an entirely consistent picture can be developed relating soil strength to various aspects of growth of underground plant parts.

Consider the series of experiments, conducted in the Southern Great Plains, where a force gauge penetrometer was used to measure soil strength. The present experiment has shown that percentage of root penetration through cores of five soils decreases curvilinearly with an increase in soil strength, and that no roots penetrate the cores when strengths are greater than 25 bars. Other experiments have shown that yields of cotton on Amarillo soil (5, 6), of grain sorghum on Amarillo and Pratt soils

[5] *Ibid.*

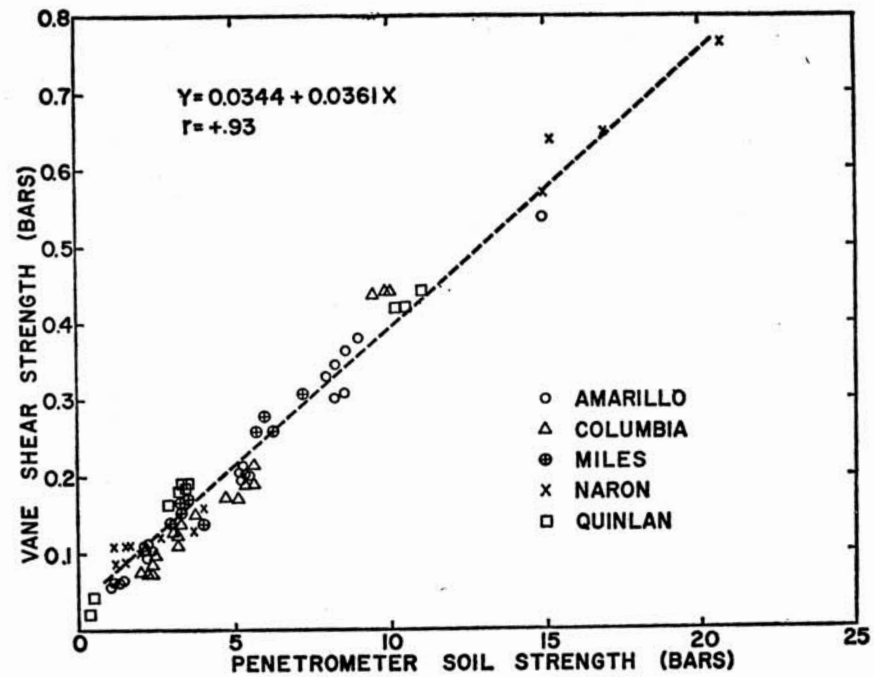

FIG. 3. Relation between soil strength as measured with a penetrometer and soil strength as measured with a laboratory vane shear apparatus.

(6), and of switchgrass[5] and sugar beets[6] on Amarillo soil are decreased progressively as soil strength, measured at field capacity, is increased to 25 bars. Increases in soil strength above 25 bars do not further reduce yields of any of the plants. Two other experiments have shown that emergence of grain sorghum and guar (3) and cotton, corn, and switchgrass[7] decreases with increases in strength of the covering soil. At about 15 to 20 bars strength, no emergence occurs even where other conditions are satisfactory.

This series of experiments has shown that the probability of root penetration through soil and of seedling emergence from soil is a function of soil strength. Results of these experiments are consistent with the working hypothesis.

Our working hypothesis states that any change in soil strength may cause a corresponding change in root exploration of a soil mass. Many of the currently designed plant experiments will alter soil strength along with the desired variable. Experiments imposing tillage, moisture, salinity, or compaction levels are especially vulnerable to incidental changes in soil strength. These changes, if they are of sufficient magnitude, will affect plant growth. Soil suction, aeration, temperature, and nutrition of the soil are evaluated periodically in many plant-growth experiments. Effects of soil strength (often called mechanical impedance) also must be recognized and evaluated in most experiments dealing with plant-soil interactions. It is especially important that soil strength levels be measured periodically in the medium- to coarse-textured soils located in environments similar to the southern half of the United States.

SUMMARY AND CONCLUSIONS

The hypothesis, that a specific change of soil strength will cause a specific response of underground plant parts, provided some other growth factor does not become limiting, is presented. Data to evaluate this hypothesis were collected by studying the relation between soil strength and cotton taproot penetration through cores of four medium- to coarse-textured soil materials.

Although slight differences among the four soil materials were apparent, root penetration percentage was reduced drastically as soil

[6] Unpublished data, Southwestern Great Plains Research Center, Bushland, Texas.

[7] *Ibid.*

strength increased to 25 bars. No taproots penetrated through cores with strengths greater than 25 bars, regardless of the soil material.

Further experiments are needed to fully evaluate the working hypothesis. The data collected to date, however, show that interpretations of many plant-growth experiments in contemporary literature may be biased, because of the probability that changes in soil strength occurred in conjunction with the desired changes.

REFERENCES

(1) Barley, K. P. 1962 The effects of mechanical stress on the growth of roots. J. Exptl. Botany 13: 95–110.

(2) Barley, K. P. 1963 Influence of soil strength on growth of roots. Soil Sci. 96: 175–180.

(3) Parker, J. J., Jr., and Taylor, H. M. 1965 Soil strength and seedling emergence relations: I. Agron. J. 57: 289–291.

(4) Taylor, H. M., and Gardner, H. R. 1963 Penetration of cotton seedling taproots as influenced by bulk density, moisture content and strength of soil. Soil Sci. 96: 153–156.

(5) Taylor, H. M., and Burnett, E. 1964 Influence of soil strength on root-growth habits of plants. Soil Sci. 98: 174–180.

(6) Taylor, H. M., Locke, L. F., and Box, J. E. 1964 Pans in Southern Great Plains soils: III. Agron. J. 56: 542–545.

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